BiFluX: A Bidirectional Functional Update Language for XML

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Different XML formats are widely used for data exchange and processing, being often necessary to mutually convert between them. Standard XML transformation languages, like XSLT or XQuery, are unsatisfactory for this purpose since they require writing a separate transformation for each direction. Existing bidirectional transformation languages mean to cover this gap, by allowing programmers to write a single program that denotes both transformations. However, they often 1) induce a more cumbersome programming style than their traditionally unidirectional relatives, to establish the link between source and target formats, and 2) offer limited configurability, by making implicit assumptions about how modifications to both formats should be translated that may not be easy to predict.

This paper proposes a bidirectional XML update language called BiFluX (BIdirectional Functional Updates for XML), inspired by the Flux XML update language. Our language adopts a novel bidirectional programming by update paradigm, where a program succinctly and precisely describes how to update a source document with a target document in an intuitive way, such that there is a unique “inverse” source query for each update program. BiFluX extends Flux with bidirectional actions that describe the connection between source and target formats. We introduce a core BiFluX language, and translate it into a formally verified bidirectional update language BiGUL to guarantee a BiFluX program is well-behaved.

1 Introduction

Nowadays, various XML formats are widely used for data exchange and processing. Since data evolves naturally over time and is often replicated among different applications, it becomes frequently necessary to mutually convert between such formats. However, traditional XML transformation languages, like the XSLT and XQuery standards of the World Wide Web Consortium (W3C), are unsatisfactory for this purpose as they require writing a separate transformation for each direction.

Bidirectional transformation (BX) languages [6] mean to cover this gap, by allowing users to write a single program that can be executed both forwards and backwards, so that consistency between two formats can be maintained for free. A variety of bidirectional languages have emerged over the last 10 years to support bidirectional applications in the most diverse computer science disciplines [6], including functional programming, software engineering, and databases. These languages come in different flavors, including many focused on the transformation of tree-structured data with a particular application to XML documents [14][3][16][7][20][9][13], and can be classified into three main paradigms. The first relational paradigm [14][3] prescribes writing a declarative (non-deterministic) consistency relation between two formats, from which a suitable BX is automatically derived. The second bidirectionalization paradigm [16][7][18] asks users to write a transformation in a traditional unidirectional language,
which plays the role of a functional consistency relation. The last combinatorial paradigm [20][9][13] encompasses the design of a domain-specific bidirectional language in which each combinator denotes a well-behaved BX, allowing users to write correct-by-construction programs by composition.

As most interesting examples of BXs are not bijective, there may be multiple ways to synchronize two documents into a consistent state, introducing ambiguity. Despite this fact, bidirectional languages are typically designed to satisfy fundamental consistency principles, and support only a fixed set of synchronization strategies (out of a myriad possible) to translate a (non-deterministic) bidirectional specification — the syntactic description of a BX — into an executable BX procedure. This latent ambiguity often leads to unpredictable behavior, as users have limited power to configure and understand what a BX does from its specification. Even for combinatorial languages, which have the theoretical potential to fully specify the behavior of a BX [8][22], their lower-level programming style requires significant effort and expertise from users to write intricate BXs via the composition of simple, concrete steps; they also scale badly for large formats, since one must explicitly describe how a BX transforms whole documents, including unrelated parts.

In this paper, we propose a novel bidirectional programming by update paradigm, in which the programmer writes an update program that describes how to update a source document to embed information from a target document, and the system derives a query from source to target that expresses the consistency between both documents. Such a bidirectional update describes the relationship between source and target documents in a simple way — as in the relational paradigm — by saying which related source parts are to be updated, but combined with additional actions that supply the missing pieces to eliminate the ambiguity in how target modifications are reflected — as in the combinatorial paradigm. For a wide class of BXs usually known as lenses [8], which have a data flow from source to view, this paradigm opens a new axis in the BX design space that enjoys a unique trade-off between the declarative style of relational approaches and the stepwise style of combinatorial approaches. This paper demonstrates that a bidirectional update language, featuring a hybrid programming style, can render bidirectional programming more user friendly.

From a linguistic perspective, the main contribution of this paper is conceptual: we propose the idea of extending an update language with bidirectional features to write, directly and at a nice level of abstraction, a view update translation strategy which bundles all the necessary pieces to build a BX. Concretely, we design BiFux, a declarative and expressive language for the bidirectional updating of XML documents that is deeply inspired by Flux [4], a simple and well-designed functional XML update language. We lift unidirectional Flux updates to bidirectional BiFux updates by imbuing them with an additional notion of view. Reading updates as BXs will motivate a few language extensions to original Flux, and require a suitable bidirectional semantics and extra static conditions on BiFux programs to ensure that they build well-behaved BXs.

This is an extended version of our original paper [23]. We have made two improvements on the original BiFux: 1) A new adaption mechanism, which is useful when the source is incompatible with the view, and needs to be adapted to a compatible one while still keeping necessary information of the original source. This mechanism plays an important role in Zhu et al.’s work [26]. 2) BiFux was implemented by a putback-based combinatorial language called putlenses [22]. However, the translation was hard to understand and the BX properties were not formally verified. We compile BiFux into our newly developed bidirectional core update language BiGul [15], which has been fully formally verified in the dependently typed language Agda [19].

The rest of the paper is organized as follows. We explain the novel features of BiFux with a representative running example in Sec. 2. High-level BiFux programs are first normalized (desugared) into the core BiFux language, presented in Sec. 3, which is a streamlined version of the high-level BiFux syntax and is easier to compile. Sec. 4 introduces the underlying engine BiGUL, and Sec. 5 discusses the compilation of core BiFux to BiGUL. Sec. 6 compares our approach with related work on bidirectional and XML programming, and Sec. 7 concludes with a summary of the main ideas and
directions for future work.

2 Syntax, informal semantics, and general framework

This section explains the syntax and informal semantics of BiFlux with a typical example, and then shows the big picture of our general framework.

2.1 Our running example

Consider a typical address book whose format is represented by the DTD from Fig. 1. An address book contains a list of people, each possessing a name, an email address, and the person’s affiliation. Let us start with the following XML address book with three people:

```xml
<addrbook>
  <person>
    <name>Hugo Pacheco</name>
    <email>hpacheco@nii.ac.jp</email>
    <affiliation>NII</affiliation>
  </person>
  <person>
    <name>Josh Ko</name>
    <email>joshko@ox.ac.uk</email>
    <affiliation>Oxford</affiliation>
  </person>
  <person>
    <name>Zhenjiang Hu</name>
    <email>zh@nii.ac.jp</email>
    <affiliation>NII</affiliation>
  </person>
</addrbook>
```

On the other hand, the NII’s administrative services may keep only a view with the name and email address of employees (people who are affiliated to NII), as shown in the DTD from Fig. 2. We have a view that simply keeps the email of each person working at NII:

```xml
<!DOCTYPE niibook [
  <!ELEMENT niibook (employee*)>
  <!ELEMENT employee (name,email)>
  <!ELEMENT name (#PCDATA)>
  <!ELEMENT email (#PCDATA)>]
```

```xml
<niibook>
  <employee>
    <name>Hugo Pacheco</name>
    <email>hpacheco@nii.ac.jp</email>
  </employee>
  <employee>
    <name>Zhenjiang Hu</name>
    <email>zh@nii.ac.jp</email>
  </employee>
</niibook>
```

We can perform update operations on this view XML. For instance, we can add Tao (in alphabetical order) as a new NII employee, fix Zhenjiang’s email, and delete Hugo:

```xml
<niibook>
  <employee>
    <name>Tao Zan</name>
    <email>zantao@nii.ac.jp</email>
  </employee>
  <employee>
    <name>Zhenjiang Hu</name>
    <email>zhenjhu@nii.ac.jp</email>
  </employee>
</niibook>
```

Now the updated view and source XMLs become inconsistent, and we need to update the source XML to restore consistency. We can write a simple program in BiFlux to describe how the update should proceed, which is shown in Fig. 3†..

The program has a single procedure `niibook`, which consists of a single UPDATE FOR VIEW statement specifying how to update the source using the view. It focuses on a sequence of people in the source by traversing down the path $source/person$, selecting only those that work at NII through the WHERE expression, and also focuses on a sequence of employees in the view by traversing down the path $view/employee$. Elements in the two sequences are matched by their names, as specified

† The names $s:elem$ and $v:elem$ are BiFlux type variables that refer to the types of source and view elements declared in the respective DTDs.
PROCEDURE niibook($source AS s:addrbook, $view AS v:niibook) =
UPDATE person[$sname AS s:name, $semail AS s:email, $saffil AS s:affiliation] IN $source/person BY
{ MATCH -> REPLACE $semail WITH $vemail
  | UNMATCHS -> DELETE .
} FOR VIEW employee[$vname AS v:name, $vemail AS v:email] IN $view/employee
MATCHING SOURCE BY $sname VIEW BY $vname
WHERE $saffil/text() = "NII"

Fig. 3 BiFluX update for the institutional address book example.

Stmt ::= Upd [WHERE Conds] | Stmt ; Stmt
Conds ::= Expr [: Conds]
IF Expr THEN Stmt ELSE Stmt
Cases ::= Pat -> Stmnt
CASE Expr OF { Cases }
P(Path, Expr)
WHERE

Upd ::= INSERT (BEFORE | AFTER) PatPath VALUE Expr
| INSERT AS (FIRST | LAST) INTO PatPath VALUE Expr
| DELETE [FROM] PatPath
| REPLACE [IN] PatPath WITH Expr
| UPDATE PatPath BY Stmnt
| UPDATE PatPath BY VStmt
| FOR VIEW PatPath [Match]
| CREATE VALUE Expr
VStmt ::= { VStmt } | VUpd
VUpd ::= MATCH -> Stmnt
VUpd ::= UNMATCHS -> Stmnt
VUpd ::= UNMATCHV -> Stmnt
Match ::= MATCHING BY Path
| MATCHING SOURCE BY Path VIEW BY Path

PatPath ::= [Pat IN] Path

Fig. 4 Concrete syntax of BiFluX updates.

by the MATCHING condition. Both the source and view elements are decomposed by pattern matching. A matching person-employee pair is processed according to the MATCH clause, updating the person’s email with the employee’s email. If an unmatched employee exists in the view, according to the UNMATCHV clause, a new person will be created in the source. We do not need to fill in the name with $vname and email with $vemail, as the underlying semantics will pass the newly created source person into the MATCH clause, and thus both the name and email will be updated with the corresponding view elements. (Although the MATCH clause does not include a statement REPLACE $sname WITH $vname, this statement in fact will be derived from the MATCHING condition and implicitly inserted.) If an unmatched person exists in the source, the person will be deleted, according to the UNMATCHS clause. This UPDATE FOR VIEW syntax is specifically designed for specifying flexible alignment strategies in update programs, and can be regarded as a novel feature of BiFluX.

2.2 Syntax and informal semantics of BiFluX

In this section we will explain the syntax and informal semantics of BiFluX in terms of the running example in Fig. 3. The syntax for BiFluX's main constructs is defined in Fig. 4, which is based on Flux [4], a high-level, purely functional language for writing XML updates. Statements Stmt include updates, composition, conditionals, let-binding, case expressions, and procedure calls. Update statements Upd include insertion, deletion, replacement, update under a path (UPDATE BY), update of a source using a view (UPDATE FOR VIEW), and
source creation. They may be guarded by a WHERE clause that defines a set of conditions constraining when the updates are executed.

In general, a BiFluX update is executed for a particular source and view as follows: by evaluating a source path or performing pattern matching on the current source, we obtain a source focus selection, which is recursively updated using a view focus selection computed by evaluating a view path or performing pattern matching on the current view, until all the view information is embedded into the source. View and source focus selections denote the parts of the source and view that can be respectively updated and used by the update.

Below we will go through each of the constructs.

2.2.1 Procedure

In BiFluX, large bidirectional update programs are constructed by using a list of small procedures. A procedure is defined in the following syntax:

\[
\text{PROCEDURE } P(\text{Var AS } \tau, \text{Var AS } \tau) = \text{Stmt} \]

The first argument is the source and the second one is the view. \(\tau\) is a regular expression type (whose details will be presented in Sec. 5.1).

In the running example, we declare a procedure named niibook with source argument \(\$source\) and view argument \(\$view\), whose types are \(s: \text{addrbook}\) and \(v: \text{niibook}\) respectively. XML element names appearing in types (in this case \(\text{addrbook}\) and \(\text{niibook}\)) are prefixed with either \(s: \) or \(v: \) to specify that they are from the source or view DTD, since there may be elements with the same name but different definitions in the source and view DTDs.

2.2.2 Path

In BiFluX, we use a subset of XPaths to traverse XML data. We omit the detailed definition of XPaths in the paper for brevity, only giving explanations in terms of a couple of paths used in the running example instead. For one, the path \(\$source/\text{person}\) extracts all the three people under \(\$source\), which points to an \(\text{addrbook}\), and produces:

\[
\text{<person>}
\text{name}Zhenjiang Hu</text>
\text{email}zh@nii.ac.jp</text>
\text{affiliation}NII</text>
\text{</person>}
\]

Function \(\text{text()}\) extracts text information. For example, \(\text{affil/text()}\) gets the text in the \(\text{affiliation}\) element pointed to by \(\text{affil}\): If \(\text{affil}\) points to \(\text{affiliation} = \text{NII}</affiliation>\), then the result will be “NII”.

2.2.3 Pattern

BiFluX supports pattern matching, which is a very useful feature of XML transformation languages like XDuce [12] or CDuce [2], allowing matching tree patterns against the input data to transform it into an output of different shape. Typical XML update languages like XQuery! [10] or FLUX [4] do not support pattern matching, since it is not essential and may be more difficult to optimize, and they use solely paths to navigate to the portions of the input documents that are to be updated in-place. On the other hand, pattern matching in BiFluX can be used to guide the update based on the structure of the data.

Our pattern language follows that of XDuce [12]:

\[\text{pat ::= } x \text{ as } \tau \mid \tau \mid c \mid () \mid n[\text{pat}] \mid \text{pat}, \text{pat}^\prime\]

A pattern can be a variable pattern restricted by a regular expression type \(\tau\), a type pattern \(\tau\), a constant pattern \(c\) representing constant values, an empty pattern (), an element pattern, or a sequence pattern. We require every variable to be annotated with a type; this simplifies our design, but will also increase the number of (often unnecessary) annotations in our update programs. We see it as an orthogonal problem that can be mitigated using existing tree-based type inference algorithms [25]. To reduce complexity, we impose a simple but strong syntactic linearity restriction on patterns (no alternative choice, no Kleene star) to ensure that matching a value against a pattern binds each variable exactly once. (Note that the restriction is imposed on patterns rather than on types, so we can still annotate patterns with alternation and sequence types.) Less severe linearity restrictions are actually known [11], but these simple patterns suffice for our practical needs.

For example, the pattern used in our running example:

\[
\text{person[}$\text{name AS } s: \text{name}, \text{email AS } s: \text{email}$,}
\]
decomposes a person element into three parts: $sname$, $s$email and $s$affil.

2.2.4 Source and view matching

The main difference between FLUX and BiFluX is that updates on sources can use view information. Such an update is performed by a new UPDATE FOR VIEW operation, which synchronizes elements in the results of evaluating a source path and a view path. In the running example, we update a list of people denoted by $s$source/person with a list of employees denoted by $s$view/employee. The Pat IN Path notation is used to decompose the elements in the two lists, so that we can specify further updates on the sub-elements.

One of the key design issues for the bidirectional-programming-by-update paradigm is to invent a nice syntax for describing flexible alignment strategies, and our solution is the UPDATE FOR VIEW operation. Such an update is performed by a new UPDATE FOR VIEW operation, which synchronizes elements in the results of evaluating a source path and a view path. In the running example, we update a list of people denoted by $s$source/person with a list of employees denoted by $s$view/employee. The Pat IN Path notation is used to decompose the elements in the two lists, so that we can specify further updates on the sub-elements.

2.2.5 Flux operations

Some update operations are inherited from the FLUX language developed by Cheney [4], and can update single XML trees or update the children of the selected tree. For example, the statement

\[\text{REPLACE $s$email WITH $v$email} \]

replaces an email element pointed to by $s$email with another email element pointed to by $v$email, while the statement

\[\text{REPLACE IN $s$email WITH 'zantao@nii.ac.jp'} \]

replaces the string wrapped inside the email element pointed to by $s$email with the string 'zantao@nii.ac.jp'. For other operations like insertion (INSERT BEFORE/AFTER) and deletion (DELETE, DELETE FROM), we refer the reader to Cheney’s work.

2.2.6 Source adaptation

Different from the first version of BiFluX, case statements have been extended to include a source adaptation mechanism. With the first version of BiFluX, if a source is not compatible with the given view, we can only throw away the source and create a new one from the view. Sometimes, however, we do want some information in the old source to be preserved in the new one. The source adaptation mechanism is added for this purpose: when incompatibility arises, the old source can be transformed to a new one compatible with the view, while keeping part of the original source information.

To illustrate how source adaptation works, consider the following scenario: The source is a record about either a book or a magazine that contains the title, authors, price, and publication year, e.g.,

\[
\begin{align*}
\text{book} & \\
\text{title} & \text{Everyday Italian} \\
\text{author} & \text{Giada De Laurentiis} \\
\text{year} & 2005 \\
\text{price} & 30.00
\end{align*}
\]

and there is a variable $s$ pointing to the above record. The view can be either a book or a maga-
zine with only the title and price, e.g.,

```xml
<magazine>
  <title>Everyday Italian</title>
  <price>15.00</price>
</magazine>
```

Suppose that we have decomposed the above view with the pattern `magazine[$v:title AS v:title, $v:price AS v:price]`. The following BiFluX program with `source adaptation` can transform the source into a `magazine` and then update it with the view values:

```bi扶西
CASE $s of
  REPLACE $s:price WITH $v:price
  book[$s:title, $s:ars AS s:author+, $s:y AS s:year, $s:price] -> ADAPT SOURCE BY CREATE VALUE
  <magazine><title/>{$s:ars} {$s:y}<price/></magazine>
```

Since the source is a book, it matches the second, adaptive branch and is transformed to a magazine with the author and year information preserved in the new source. After encountering an adaptive branch and executing the associated transformation, the case statement will be run again on the new source, which, in this case, is a magazine and matches the first normal branch. The replacement statements are then executed, producing the following updated source:

```xml
<magazine>
  <title>Everyday Italian</title>
  <author>Giada De Laurentiis</author>
  <year>2005</year><price>15.00</price>
</magazine>
```

The programmer should adapt the source with the intention of making it match with a normal branch — to avoid falling into adaptive branches repeatedly and resulting in non-termination, the underlying engine BiGUL will check that the adapted source matches a normal branch; subsequently, the adapted source will be updated by the bidirectional update statement in that branch and an updated source will be generated.

### 2.3 Bidirectional execution

Although the emphasis is on writing updates, BiFluX programs have a bidirectional interpretation. They can be read as 1) an *update function* $U(s, v') = s'$ that updates a source $s$ into a new source $s'$ which contains a given view $v'$, or 2) a *query function* $Q(s) = v$ that computes a view $v$ from a given source $s$; these functions may be partial. For the running example in Fig. 3, (assuming that people are uniquely identified by their names) the query function is semantically equivalent to the XQuery expression:

```xml
<niibook>
  {for $person in $s/person where $person/affiliation/text() = "NII"
   return <employee>
     {$person/name}
     {$person/email}
   </employee>
  }
</niibook>
```

For example, a typical use case is to run the BiFluX program as a query on the source in Sec. 2.1 and get the first view in that section, which is then modified to the second view. To produce a new, consistent source, the BiFluX program is run as an update on the original source and the modified view. In the new source, Josh is left unchanged, Tao is created with the default affiliation NII (as his name does not match any name in the original source), Zhenjiang's email is updated, and the Hugo is deleted:

```xml
<addrbook>
  <person>
    <name>Zhenjiang Hu</name>
    <email>zhenjhu@nii.ac.jp</email>
    <affiliation>NII</affiliation>
  </person>
</addrbook>
```

Note that it is possible to preserve information in the original source (in this case Josh's information) since in a update program we can choose to update only part of the source and keep everything
else. This is not always supported by “bidirectional” XML transformation languages: biXid [14], for example, supports transformation of one XML format into the other and vice versa, creating a new XML document from scratch every time; consequently, when biXid converts a more informative format $F_1$ into a less informative format $F_2$, the information exclusive to $F_1$ will be lost and cannot be recovered when converting a $F_2$-formatted document back to $F_1$.

Our language is carefully designed to ensure that the inferred relationship between sources and views is deterministic, so that capturing it by a query function is appropriate. In other words, there exists a unique query function for each update program written in our language. Moreover, its bidirectional semantics satisfies two basic synchronization properties: that an update $U$ consistently embeds view information to the source: $U(s, v') = s' \Rightarrow Q(s') = v'$ UPDATEQUERY and that it does not update already consistent sources: $Q(s) = v \Rightarrow U(s, v) = s$ QUERYUPDATE These two properties are commonly known as the well-behavedness laws of lenses in the bidirectional programming community [6].

The UPDATEQUERY property indicates that view information must be fully embedded into the source and cannot be arbitrarily discarded. This calls for careful language design that helps the programmer to manage view information and check that the view is indeed fully embedded. In BiFLuX, full embedding is checked during compilation to guarantee that the view can be reconstructed from the source. For example, if we write an empty statement ({})) in the MATCH clause of the running example instead of REPLACE $v$email WITH $s$email, the program will fail to compile, as it will be discovered that the view variable $v$email is not used and hence not embedded into the source.

Sometimes a part of the view contains only redundant information in the sense that it can be computed from other parts, and hence does not need to be embedded. This situation can be explicitly described with a WHERE clause. For example, suppose that in the view we include for each name some extra indexing information that can be derived from the name, and this indexing information is not present in the source. At some point in the BiFLuX program for synchronizing this kind of source and view, we might have two view variables $v$name and $v$index, denoting a name and an associating indexing information. We can embed $v$name into the name part of the source, but cannot do so for $v$index, since $v$index does not have a corresponding part in the source. In this case, we indirectly embed $v$index into the source by specifying the dependency between $v$index and $v$name as follows: WHERE $v$index := $v$index[$v$name]. After that, $v$index is considered embedded, and we only need to embed $v$name into the source.

2.4 Other update strategies

In this section, we show that BiFLuX is flexible enough for describing other update strategies that may better reflect the user’s intention.

For the running example we have explained, even though the BiFLuX program in Fig. 3 gives a reasonable update strategy for many situations, this strategy is not the only one possible; for example, deleting a person from the view may actually mean that the person just moves to another institute instead of disappearing from the source database. We can easily describe this alternative update strategy by modifying the UNMATCHS case, as shown in Fig. 5.

Running this second update moves people like Hugo to a new institute, in this case “NCI”, producing the updated source:

```xml
<addrbook>
  <person>
    <name>Hugo Pacheco</name>
    <email>hpacheco@nii.ac.jp</email>
    <affiliation>NCI</affiliation>
  </person>
  <person>
    <name>Josh Ko</name>
    <email>joshko@ox.ac.uk</email>
    <affiliation>Oxford</affiliation>
  </person>
  <person>
    <name>Tao Zan</name>
    <email>zantao@nii.ac.jp</email>
    <affiliation>NII</affiliation>
  </person>
  <person>
    <name>Zhenjiang Hu</name>
    <email>zhenjhu@nii.ac.jp</email>
    <affiliation>NII</affiliation>
  </person>
</addrbook>
```
PROCEDURE niibook($source AS s:addrbook, $view AS v:niibook) =
UPDATE person[$sname AS s:name, $semail AS s:email, $affil AS s:affiliation] IN $source/person BY
{ MATCH -> REPLACE $semail WITH $vemail |
UNMATCHV -> CREATE VALUE
<person><name/><email/></p>
| UNMATCHS -> REPLACE IN $affil WITH "NCI" }
FOR VIEW employee[$vname AS v:name, $vemail AS v:email] IN $view/employee
MATCHING SOURCE BY $sname VIEW BY $vname
WHERE $affil/text() = "NII"

Fig. 5  Another update strategy in BiFluX.

For simplicity, we omit updating his email address accordingly in the BiFluX program. In general, we can describe even more complicated strategies like conditionally delete or modify the person’s information in the UNMATCHS clause.

This behavior cannot usually be described using the typical BX languages (e.g. lenses [8]), which are designed from the perspective of get, as they only provide one default update strategy for the put direction, usually reflecting deletion on the view to deletion on the source, and the user has no way of specifying a different update strategy for the put direction.

The main difference between BiFluX and Foster’s lenses [8] is that the emphasis is now on writing a put transformation instead of a get transformation. This will allow a much more flexible and intuitive control over backward synchronization strategies, by making several put design choices explicit in the design of a bidirectional update.

2.5 General framework

The general architecture of our bidirectional updating framework is illustrated in Fig. 6. A BiFluX program is evaluated in two stages. First, it is statically compiled against a source and a view schema (represented as DTDs), producing a bidirectional executable. The generated executable can then be evaluated bidirectionally for particular XML documents conforming to the DTDs: in forward mode as a query $Q$, or in backward mode as an update $U$.

The compilation of BiFluX has two stages: The high-level BiFluX language is first normalized into a clean core language with syntax simplification, and then the core language is compiled into an XML-oblivious language BiGUL. The second stage is the key part that includes handling XML values and regular expression types, checking necessary bidirectional transformation constraints and bidirectionalizing the core language by dealing with paths, composition etc. We will explain the core language, introduce BiGUL, and describe the compilation rules from core to BiGUL in the following sections.

3 Core Language

The high-level language presented in Sec. 2 has a user-friendly syntax, but its operations are overlapping and complex. Following the design of Flux and as standard for many other languages, we introduce a core update language of canonical operations whose semantics are easier to define, and high-level BiFluX are normalized into this core language.

To give the reader a taste of the core language, the core program for the address book running example is shown in Fig. 7. Roughly speaking, it traverses down a source path $source/child/::person$ to get a list of people, then retrieves all the employees by the view path $view/child/::employee$, and finally uses a six-argument alignkey operation to
$source / child / :: \text{person}$

\[
\begin{align*}
(\text{case self of} & \quad \text{person} \ [\text{\$sname as } s : \text{name}, \text{\$semail as } s : \text{email}, \text{\$affiliation as } s : \text{location}] \to \\
& \quad \text{\$affiliation / child / :: text()} = "\text{NII}") \\
(\text{case self of} & \quad \text{person} \ [\text{\$sname as } s : \text{name}, \text{\$semail as } s : \text{email}, \text{\$affiliation as } s : \text{affiliation}] \to \text{\$sname}) \\
(\text{case self of} & \quad \text{employee} \ [\text{\$vname as } v : \text{name}, \text{\$vemail as } v : \text{email}] \to \text{\$vname}) \\
(\text{case self of} & \quad \text{person} \ [\text{\$sname as } s : \text{name}, \text{\$semail as } s : \text{email}, \text{\$affiliation as } s : \text{affiliation}] \to \\
& \quad \text{caseV self of} \\
& \quad \text{employee} \ [\text{\$vname as } v : \text{name}, \text{\$vemail as } v : \text{email}] \to \\
& \quad \text{\$semail ([\text{replace}] \text{\$vemail};} \\
& \quad \text{\$sname ([\text{replace}] \text{\$vname})} \\
& \) \\
& \text{(insert person [name [""], email [""], affiliation [""NII""]]}) \\
& \text{delete} \\
& \text{$view / child / :: employee$}
\end{align*}
\]

Fig. 7 Core program of the institutional address example in Fig. 3.

update this list of people by the list of employees.

3.1 Bidirectionalizable updates

Unlike conventional XML update languages, our core update language mainly consists of bidirectionalizable updates. Their names suggest what their update semantics are, but in Sec. 5 they will be interpreted as BXS [15] that update a source document given a view document or query a source document to compute its view fragment. The grammar of core bidirectionalizable updates $b$ is as follows:

\[
b :: = \text{skip} \mid \text{fail} \mid \text{replace} \mid p[b] \mid \text{[b]} \varepsilon_v \mid b; b'
\]

\[
| \text{alignpos ef } b c r \\
| \text{alignkey ef } e_{ns} e_{mv} b c r \\
| \text{caseS p of } \text{pat} \to b \mid a \\
| \text{caseV e_v of } \text{pat} \to b \\
| \text{ifS e then } b \text{ else } b' \\
| \text{ifV e then } b \text{ else } b' \\
| \text{iter } b \mid \text{view } x := e_v \text{ in } b \mid P(p_s, e_v)
\]

We will informally describe their update semantics below.

The operation skip keeps the source unchanged provided that the view is empty, the fail operation aborts an update, and the replace operation replaces the source with the view.

The operation $p[b]$ traverses the source along a source path $p$, and runs a further update $b$ on the sub-source. For example, in Fig. 7, we have a source path $\text{$source / child / :: person$}$ followed by a slightly complex bidirectional update $b$. After evaluation of this source path, the source will be a list of people, and $b$ is run on this list.

Dually, the operation $[b] e_v$ changes the current view by evaluating an expression $e_v$ on it and uses the result as the new view for the update $b$. In Fig. 7, after evaluation of the expression on the last line, i.e. the path $\text{$view / child / :: employee$}$, the view for the inner alignkey will be a list of employees.

Composition $b_1 ; b_2$ updates a part of the source with $b_1$, and another part of the source with $b_2$. To guarantee the \text{UPDATEQUERY} property, the same part of the source cannot be updated twice. This is enforced by requiring that the two statements $b_1$ and $b_2$ update different source variables. For example, in Fig. 7, we have a composition statement as follows:

\[
\text{\$semail ([\text{replace}] \text{\$vemail);} \\
\text{\$sname ([\text{replace}] \text{\$vname)}
\]

Each one is in the form of $p[[b] e_v]$. The first one replaces source email ($\text{\$semail}$) with view email ($\text{\$vemail}$), and the second one replace source name...
We can use delete which evaluates to a boolean, and match source elements satisfying by position (alignpos) or by key (alignkey). In the latter case, keys are computed from the source and view respectively by evaluating two expressions $e_{ms}$ and $e_{mv}$. In Fig. 7, the three expressions $e$, $e_{ms}$, and $e_{mv}$ for the alignment operation (alignkey) are case expressions. Since $e$, $e_{ms}$ are evaluated on the source, the self in $e$ and $e_{ms}$ refers to the current source element (i.e. a person), while the self in $e_{mv}$ refers to the current view element (i.e. an employee).

After aligning the source sequence with the view sequence, there are three cases to consider: For matched source–view element pairs, we use a bidirectionalizable statement $b$ to synchronize them; for an unmatched view, we use a recover statement $r$ to either delete or transform it. Create statements $c$ are simply unidirectional updates which will be introduced in Sec. 3.3. Recover statements $r$ are enriched unidirectional updates of the form:

$$ r ::= \text{delete} | \text{u} | \text{if } e \text{ then } r \text{ else } r' \quad | \quad \text{case } e \text{ of } \text{pat} \rightarrow r $$

We can use delete for deleting an unmatched source, or unidirectional updates to modify an unmatched source so that the $e_s$ filtering expression evaluates to false.

The core language also provides two kinds of conditionals (ifs and ifv) and case statements (caseS and caseV), whose expressions or paths are evaluated on the source and view respectively. The source adaptation mechanism introduced in Sec. 2.2.6 is handled by caseS at this level, which can have adaptive branches. Case statements are used in Fig. 7 for decomposing the source and view by pattern matching.

There are still some operations that do not appear in Fig. 7. The operation iter $b$ embeds the same view into each element of a source sequence. A procedure call $P(p_s, v_o)$ updates the sub-source at the end of the source path $p_s$ using the result of evaluating the view expression $v_o$ as the view. Procedures may be recursive. The statement $\text{view } x := e_v \text{ in } b$ states that the value for a view variable $x$ can be computed from the rest of the view using the view expression $e_v$, and then runs $b$ using the remaining view.

### 3.2 Expressions and paths

In BiFlux, updates instrumentally use XQuery expressions, XPath paths and XDupe patterns to manipulate XML data. Different expressions are used for different purpose: general expressions are arbitrary which are evaluated into a value, view expressions are a subset of them that need to be invertible, and source paths are again a subset of general paths because they are used to narrow the focus.

#### 3.2.1 General expressions and paths

We write expressions $e$ in a minimal XQuery-like language, which is a variant of the $\mu$XQ core language proposed in [5]:

$$ e ::= () | e, e' | n[e] | p | \text{let } pat = e \text{ in } e' \quad | \quad e \approx e' | \text{if } e \text{ then } e' \text{ else } e'' \quad | \quad \text{for } x \text{ in } e \text{ return } e' \quad | \quad \text{case } e \text{ of } \text{pat} \rightarrow e' $$

Note that there are no case expressions in $\mu$XQ as they can be emulated by conditional expressions; we extend our expression language with case expressions to simplify the translation from the BiFlux surface language. We differentiate paths $p$ in a core path language that represents a minimal dialect of XPath:

$$ p ::= \text{self} | \text{child} | :: \text{nt} | \text{where } e | p / p' \quad | \quad x | w | \text{true} | \text{false} $$

$$ nt ::= n | \text{text()} | \text{node()} $$

To simplify the formal treatment, we consider node-tests ::nt that apply to atomic values and where clauses where $e$ that filter values satisfying an expression $e$. As syntactic sugar, we write $p :: nt \triangleq p / :: nt, p[e] \triangleq p / \text{where } e, \text{ and } p / n \triangleq p / \text{child} :: n$.

#### 3.2.2 View expressions and paths

Restrictions have to be placed on expressions used in the statement $\mathrm{|b|e}$, since such expressions should express invertible computations to allow the statement to be bidirectionalized. The allowed subset of the expressions and paths defined in Sec. 3.2.1 is as follows:

$$ e ::= () | e, e' | n[e] | p | \text{true} | \text{false} \quad p ::= x | \text{self} | \text{child} | :: nt | p / p' $$
3.2.3 Source paths
A source path $p$, as used in the statement $p[b]$, narrows the source focus to only part of the current source. Like in FLUX, not all paths can be used to change the source focus: We do not allow constant string paths ($w$) and boolean paths ($true$ and $false$), as they are meaningless for focus narrowing. Also, only the self and child axes are supported; this ensures that only descendants of the source focus can be selected as the new source focus and that a selection contains no overlapping elements. To sum up, the valid source paths are as follows:

$$p ::= x \mid self \mid child \mid nt \mid p / p'$$

3.3 Unidirectional updates
Unidirectional updates are used in the create statement of the alignment operations (alignpos and alignkey). Our core unidirectional updates are adapted from the core FLUX update language [4]:

$$u ::= skip \mid u; u' \mid \text{insert} \ e \mid \text{delete} \mid \text{if} \ e \ \text{then} \ u \ \text{else} \ u' \mid \text{case} \ e \ \text{of} \ pat \ \to \ u$$

These include standard operations such as the no-op skip, sequential composition, conditionals, and case expressions. The basic operations are insert $e$, which inserts a value given an empty sequence as focus; and delete, which replaces any value with the empty sequence. We can also apply an update in a specific direction (that traverses down a path $p$), moves to the left or right of a value, or focuses on the children of a labeled node).

3.4 BiFluX to Core Update Normalization
The translation from the high-level BiFluX language to the core language is usually referred to as normalization in languages like XQuery and FLUX. Since most translation rules are straightforward (which can be seen by comparing Fig. 3 and Fig. 7), we will only explain the special UPDATE FOR VIEW statements as shown in Fig. 8. The splitVStmt function parses a VStmt into a matching statement and two optional unmatched-view and unmatched-source statements. The matching statement is translated using $[-]_{\text{MStmt}}$ that accepts source/view patterns and paths. The source/view patterns ($\text{pat}_s$, and $\text{pat}_v$) are used to do a pattern match on the current source and view, to decompose them into smaller subparts, and the source/view paths ($\text{ps}_s$, and $\text{ps}_v$) are used to extract the source and view keys for matching; the paths are also used to generate a replace statement that updates the source key with the view key, guaranteeing that the updated source still matches with the view. The translated core expression first gives a case analysis on the current source using $\text{pat}$ and view using $\text{pat'}$, then executes the core statement normalized form surface language. Optional unmatched-view statements are translated using a function $[-]_{\text{MStmt}}(\text{mpat})$ that takes an extra optional view pattern and returns a core create update; Optional unmatched-source statements are
translated using a function \([-]\)Mstmt\(\bigcup\text{'}\) that takes an extra optional source pattern and returns a core recover update; if no UNMATCHS clause is defined, all unmatched source elements are deleted by default.

The translation denotes a partial function from high-level BiFluX to core BiFluX. For example, INSERT is not supported for bidirectional updates, UPDATE FOR VIEW is not supported for unidirectional updates, and CREATE is only supported under UNMATCHV or UNMATCHS clauses, respectively. We assume that paths and expressions are expressed in terms of our core languages; this is standard practice as normalization of XQuery expressions or XPath paths can be done independently.

4 BiGUL

The core language presented in Sec. 3 still retains XML-specific details from the high-level BiFluX and freely uses pattern matching and variables to manage data-flow, making it difficult to directly give a formal bidirectional semantics to the language. To achieve bidirectionality more reliably, we designed a generic bidirectional update language BiGUL [15], in which the data representation is XML-free and the data-flow management is done in a point-free style. One of the design goals of BiGUL is to serve as the underlying engine for BiFluX — we will compile the core language into BiGUL in Sec. 5. The advantage of using BiGUL is that it is completely formally verified in the dependently typed language Agda [19] to guarantee that any program written in BiGUL satisfies the BX properties. We have ported it into Haskell as an embedded domain-specific language, and the compilation rules in Sec. 5 can freely use Haskell’s language features to produce BiGUL programs.

The syntax of BiGUL is shown in Fig. 9, which originates from BiFluX’s core language, and thus many operations — e.g., Replace, Fail, and Skip — resemble those presented in Sec. 3.1. In this section, we will mainly focus on the operations that are different from the core language.

One important new operation is Update, which is used to decompose a source into parts by pattern matching, and then update each part by a separate BiGUL program. The patterns used are called update patterns (upat): UVar updates the current source with a bigul statement, UIn updates the children of the current source, UProd decomposes the source into a product of two parts and updates each part separately, UConst matches the current source with a given value, and ULeft and URight handles the situation in which source is a choice. The view for the Update operation should have the same structure as the update pattern; to rearrange the view into that structure, a new operation RearrV is introduced, which computes a new view by a simple invertible function (like what \([e]b\) does). Sometimes the source also needs to be rearranged for updating, so a dual operation RearrS is introduced.

Here is a small example about Update and RearrV. Suppose that the source is a piece of personal information which have name, email, and affiliation as its children, and a view that is a pair of name and email. If we want to update the source’s name and email with the information from view, we can write a BiGUL program like this:

\[
\text{RearrV} \\
(\lambda(vname, vemail) \rightarrow (vname, (vemail, ())))) \\
(\text{Update} (\text{UIn} (\text{UProd} (\text{UVar Replace}))) \\
(UProd (\text{UVar Replace})) \\
(\text{UVar Skip})))
\]

We first rearrange the view pair \((vname, vemail)\) into a triple, adding an empty view element at the end in order to match with the update pattern (also matching a triple), then update the source by using UIn in order to update its children, which is a product of elements, and finally decompose the product.
by two UProd patterns. After the source is decomposed into a triple, we update the replacements Replace, Replace, and Skip associated with the UVar patterns to replace the name and email and leave the affiliation unchanged.

The Align operation in BiGUL unifies the two core operations alignpos and alignkey into one, based on the observation that alignpos can be regarded as a special case of alignkey that uses position as the key. The boolean filter function corresponds to $e_f$, while the boolean match function specifies when a source and view element are matched. The remaining three arguments deal with the three cases arising from source–view alignment: the bigul program deals with matched pairs, the create function creates a new source from an unmatched view element, and the conceal function deletes or modifies an unmatched source element.

CaseS and CaseV are two kinds of case analysis on either source or view. They differ from their counterparts in the core in two aspects: BiGUL’s CaseS and CaseV always match the whole source or view with the branches, and the source or view is fed into a boolean function (predicate) to decide whether it matches a branch. BiGUL does not include conditionals like ifS and ifV in the core, since they are subsumed by CaseS and CaseV.

## 5 Core Compilation

The core language is compiled into BiGUL, which is the most complex part of this work since details about XML and bidirectionality are dealt with here. For the address book running example, the normalized core program in Fig. 7 is compiled into the BiGUL program in Fig. 10. The compilation (Sec. 5.2) basically consists of five parts: translating the core bidirectionalizable updates to BiGUL operations (Sec. 5.2.3, Sec. 5.2.4, and Sec. 5.2.5), source paths into BiGUL update patterns (Sec. 5.2.1), view expressions into BiGUL’s view rearrangement operation (Sec. 5.2.2), general expressions into Haskell expressions (Sec. 5.3), and unidirectional updates into Haskell functions. The more interesting part is, naturally, the translation of the bidirectionalizable updates, and we will devote this section to this part. The translation of the unidirectional updates is straightforward and in fact tedious, so we omit them in this paper for brevity.

We should emphasize that we intend the compilation rules to serve as the (preliminary) definition of BiFluX semantics. That is, instead of defining a semantics for the surface language and then proving that the compilation rules preserve the semantics, we will rely on the intuitive understanding of what BiFluX programs should do—as presented in Sec. 2—and capture that intuition with the compilation rules. Admittedly, it is hard to make a semantics defined by compilation as clear as one hopes for, but such a semantics is usually sufficient for an experimental language. Our main purpose of designing BiFluX is to experiment with the paradigm of bidirectional programming by update, and we expect to make further changes and extensions (some of which will be mentioned in Sec. 7) to the language. We plan to give a better formalization, in particular specifying a semantics for the surface language, after the language is more mature and stabilized.

What we have refrained from saying explicitly up until now is that all of the high-level BiFluX language, the core language, and BiGUL are typed. We have omitted the typing rules for the languages from the paper since they are in general straightforward. The compiler, however, sometimes needs to use type information in a core program to generate appropriate BiGUL code, and hence the compilation rules need to refer to the types. Therefore, before presenting the compilation rules, we first give an account of the type system used by the core language in Sec. 5.1.

### 5.1 XML values and regular expression types

As several other XML processing languages [12] [4] [5], we consider a type system of regular expression types with structural subtyping\(^\dagger\):

- Atomic types $\alpha ::= \text{bool} \parallel \text{string} \parallel n[\tau]$
- Sequence types $\tau ::= \alpha \parallel (\) \parallel \tau \parallel \tau' \parallel \tau, \tau' \parallel \tau^* \parallel X$

*Atomic types* $\alpha \in \text{Atom}$ are primitive booleans, strings or labeled sequences $n[\tau]$. *Sequence types* $\tau \in \text{Type}$ are defined using regular expressions.

\(^\dagger\) We use $\parallel$ for syntax alternatives in the type grammar to prevent confusion.
Type definitions $\tau_D$ are sequences with no top-level variables (to avoid non-label-guarded recursion [5]). A type signature $E$ is a set of named type definitions of the form $X = \tau_D$, and is well-formed if no two types have the same name and all type variables in definitions are declared in $E$. We write $E(X)$ for the type bound to $X$ in $E$. Hereafter, we will assume the signature $E$ to be fixed.

In traditional XML-centric approaches [12][5], values are encoded using a uniform representation that does not record the structure that types impose on values. This “flat” representation is economical and simplifies subtyping, but makes it harder to realize that a value belongs to a type and therefore to integrate regular expression features into functional languages with non-structural type equivalence, such as Haskell or ML. In this paper, we instead consider a structured representation of values (in line with values of algebraic data types) that keep explicit annotations which, in a way, witness how to parse a flat value as an instance of a type [17]:

Atomic values

$$t ::= \text{true} \mid \text{false} \mid w \mid n[v]$$

Forest values

$$v ::= t \mid () \mid L \mid R \mid (v, v) \mid [v_0, \ldots, v_n]$$

Atomic values $t$ in Tree can be $\text{true}, \text{false} \in \text{Bool}$, strings $w \in \Sigma^*$ (for some alphabet $\Sigma$), or singleton trees $n[v]$ with a node label $n$. Forest values...
v ∈ Val include the empty sequence (), left- L v or right- R v tagged choices, binary sequences (v, v) and lists of arbitrary length [v₀, . . . , vₙ]. The semantics of a type τ denotes a set of values [τ] that is defined as the minimal solution (formally the least fixed point [12]) of the following set of equations:

\[
\begin{align*}
\llbracket \text{()} \rrbracket & \triangleq \{()\} & \llbracket \text{string} \rrbracket & \triangleq \Sigma^* \\
\llbracket \text{bool} \rrbracket & \triangleq \{\text{true}, \text{false}\} & \llbracket X \rrbracket & \triangleq \llbracket E (X) \rrbracket \\
\llbracket \alpha \rrbracket & \triangleq \{v \mid v \in [\tau]\} \\
\llbracket \sigma_1, \sigma_2 \rrbracket & \triangleq \{(v, v') \mid v \in [\tau], v' \in [\tau']\} \\
\llbracket \tau \mid \tau' \rrbracket & \triangleq \{L v \mid v \in [\tau]\} \cup \{R v \mid v \in [\tau']\} \\
\llbracket \tau^* \rrbracket & \triangleq \{[v₀, . . . , vₙ] \mid v₀, . . . , vₙ \in [\tau], n ≥ 0\}
\end{align*}
\]

In our context, values in the type semantics preserve the type structure. We will denote flat values ft ∈ FTree and fv ∈ FVal (dropping left/right tags, parenthesis and list brackets) by:

- Flat atomic values
  \[
  ft ::= \text{true} | \text{false} | w | n[fv]
  \]
- Flat forest values
  \[
  fv ::= () \mid ft, fv
  \]

The notion of subtyping plays a crucial role in XML approaches with regular expression types. A type τ₁ is said to be a subtype of τ₂, written τ₁ ⊆: τ₂, if the flat values belonging to τ₁ are also values of τ₂, i.e. \([\tau₁]_{\text{flat}} \subseteq [\tau₂]_{\text{flat}}\). Since we retain a structured representation of values, upcasting a value v₁ of type τ₁ into a supertype τ₂ requires more than a proof of subtyping: we must also change v₁ into a value v₂ that contains the same flat information as v₁ but conforms to the structure of τ₂. This problem has been considered in [17], that introduces a subtyping algorithm as a proof system with judgments of the form ⊢ τ₁ ⊆: τ₂ ⇒ c, that we treat as a “black box”. In BX terms, c : τ₂ ⊆→ τ₁ is called a canizer [9], which is a bit like a lens from τ₂ to τ₁ that comprises a total upcast function ucast: τ₁ → τ₂, and a partial downcast function dcast: τ₂ → τ₁. In our sense, canizers satisfy two properties stating that they only handle structure:

\[
\begin{align*}
\text{ucast } v₁ & \sim v₁ \quad \text{Up} \sim \\
\text{dcast } v₂ & = v₁ ⇒ v₁ \sim v₂ \quad \text{Down} \sim \\
\end{align*}
\]

The equivalence relation \(\sim\) used above ignores structure and relates values parsing the same data using different markup, e.g., \(L v \sim R v\); formally,

\[
v \sim v' \triangleq \text{flat}(v) = \text{flat}(v')
\]

where the function \(\text{flat} : \text{Val} \rightarrow \text{FVal}\) flattens a structured value.

### 5.2 Compilation of Bidirectionalizable Updates

We can now move on to the compilation rules from the core language to BiGUL. The first three basic operations — replace, skip, and fail — are simply compiled into their counterparts in BiGUL. The rest are explained in the following subsections.

#### 5.2.1 Source Paths

The \(p[b]\) operation in Sec. 3.2.3 updates part of the source, and in BiGUL this behavior is implemented by the Update operation. The major difference between the two operations is that the former uses a source path to point to the sub-source, while the latter uses an update pattern to decompose the source and execute a sub-update on the sub-source. A source path should thus be compiled into a “pattern with a hole”, into which we can fill in the sub-update. Since we can use whatever the host language Haskell offers to describe the compilation, we can simply express the semantics of a source path — i.e. a “pattern with a hole” — as a function mapping a BiGUL update to an update pattern. To be able to define the semantics of source paths compositionally, however, we instead compile source paths to functions mapping a pattern to another pattern, and these functions will be easily composable. After a source path is compiled into such a function, we can apply the function to UVar bigul where bigul is the sub-update. The resulting update pattern can then be supplied as the argument to an Update operation.

The compilation rules are shown in Fig. 11. Γ is an environment that maps variables to their type, and always include a special variable ‘\(\_\)’ for recording the type of the current focus which is useful for paths like self. When Γ contains only the focus, we write \(\{\tau\}\) for \(\{(\_, \tau)\}\) for simplicity.

The compilation of a variable path \((x)\) needs a helper function genupat to create an update pattern for the current environment Γ. As Γ may have more than one source variables, others except x in fact will not be updated (the special variable ‘\(\_\)’ will not be considered during this computation), and thus we use UVar Skip to skip them and combine all of them by UProd. The construction of upat from Γ follows the alphabetical order of the variables in Γ in order to keep the generation of patterns consistent. For example, suppose that we have an environment Γ = \(\{(y, τ₂), (x, τ₁)\}\) and a
\[
\Gamma \vdash_{sp} p \Rightarrow f
\]

\[
\begin{align*}
\Gamma \vdash_{sp} p & \Rightarrow f \\
\Gamma \vdash_{sp} p & \Rightarrow \text{upat}.\text{genupat}((\Gamma, x, \text{upat})) \\
\Gamma \vdash_{sp} p & \Rightarrow \text{upat}.\text{replace}((\Gamma, x, \text{upat})) \\
\Gamma \vdash_{sp} p & \Rightarrow \text{upat}.\text{replace}((\Gamma, x, \text{upat}))
\end{align*}
\]

\[
\begin{align*}
\tau & \vdash_{sp} :: \text{n} \Rightarrow \text{id} \\
\tau & \vdash_{sp} :: \text{nt} \Rightarrow \text{const} \quad \text{(UVar Skip)}
\end{align*}
\]

\[
\begin{align*}
\Gamma & \vdash_{sp} p_1 \Rightarrow f_1 \\
\Gamma & \vdash_{sp} p_2 \Rightarrow f_2
\end{align*}
\]

\[
\Gamma \vdash_{sp} p_1 / p_2 \Rightarrow f_1 \circ f_2
\]

**Fig. 11 Compilation of source paths.**

**Fig. 12 Compilation of view expressions.**
fully decompose a view into small pieces. Let us give a counter-example: Suppose that $v_{bookstore}$ contains a list of books and each book has a list of authors. The path $v_{bookstore}/book/author$ retrieves authors of all the book in $v_{bookstore}$ as a single list. This path is not invertible since, in the query direction, there is no way to determine how to divide the list of authors into sublists for the
Our next job is to compute a Haskell pattern (\(hp\)) from the above set of paths, and an environment (\(\Gamma_p\)) that maps each path to a fresh Haskell variable name, which will be used for view expression compilation. Fig. 12 gives the compilation rules for constructing a Haskell expression (\(hexp\)) from a view expression under the environment \(\Gamma_p\). The most interesting case is that when the view expression is a path \(p\), it suffices to fetch the corresponding Haskell variable name from \(\Gamma_p\)—there is no need to analyze \(p\). The view expression in our running example is a path $view / child / :: employee$, and the compiled lambda expression is \((\lambda (\text{Nhbook } \text{hEmployeelst}) \rightarrow \text{hEmployeelst})\), as shown in the third line of Fig. 10.

A related operation is $view x := e$ in $b$, which is compiled into a combination of two operations in BiGUL, as shown in Fig. 13: a view rearrangement $\text{RearrV}$ to separate $x$ from the rest of the view, and a $\text{Dep}$ operation stating that the value for $x$ can be computed from the other part.

### 5.2.3 Composition

The compilation of composition statement \(b_1; b_2\) guarantees that \(b_1\) and \(b_2\) update different parts of the source by splitting and rearranging the source into three parts, one to be updated by \(b_1\), another by \(b_2\), and the third part to be kept unchanged.

Specifically, the core composition statement \(b_1; b_2\) will be compiled into a source rearrangement (\(\text{RearrS}\)), a view rearrangement (\(\text{RearrV}\)), followed by an $\text{Update}$ operation. In the compilation rule for composition in Fig. 13, \(s\) denotes the set of source variables, while \(s_1\) and \(s_2\) are the source variables used in \(b_1\) and \(b_2\) respectively. We use an abstract notation \(s \prec ((s_1, s_2), s_3)\) for the lambda expression that rearranges a tuple of values for the variables in \(s\) to a triple whose components are values for the variables in \(s_1, s_2\), and \(s \setminus (s_1 \cup s_2)\) respectively. The view is similarly rearranged. Finally, with an $\text{Update}$, the three parts of the source are updated using the three parts of the view (the last of which is empty) by $\text{Replace}$, $\text{Replace}$, and $\text{Skip}$.

To illustrate, let us look at the composition used in the running example:

\[
\begin{align*}
\text{\$semail} & \left[\text{\text{replace}}\right] \text{\$semail}; \\
\text{\$sname} & \left[\text{\text{replace}}\right] \text{\$sname}
\end{align*}
\]

At this point, the source is of the form ($\text{\$sname, \$semail, \$affiliation}$) (which is a simplified representation for expository purpose), and the source rearranging lambda expression we synthesize is \(\lambda (\text{\$sname, \$semail, \$affiliation}) \rightarrow ((\text{\$semail, \$sname}), \text{\$affiliation})\), since the left-hand side statement updates \(\text{\$semail}\), the right-hand side statement updates \(\text{\$sname}\), and \(\text{\$affiliation}\) is untouched. Similarly the view rearrangement is synthesized, followed by the $\text{Update}$ operation. The compiled BiGUL fragment can be found in Fig. 10.

#### 5.2.4 Cases and conditionals

The source case statement is essentially compiled into $\text{CaseS}$ in BiGUL wrapped in an $\text{Update}$ due to the need to compile the source path. Each source pattern \(\text{pat}_i\) is compiled into a Haskell pattern (by the rules shown in Fig. 14), a boolean function, and a source rearrangement. An adaptive operation \(\alpha\) is compiled into a plain Haskell function which computes a new source from the current one.

The view case statement, on the other hand, is compiled into $\text{CaseV}$, along with “three” view rearrangement operations. The first rearrangement operation splits the view into those used in the view expression and the rest; the second one evaluates the expression, while keeping the rest as it is; in each branch, after matching the result of evaluating the expression with the \(\text{pat}_i\), the third rearrangement merges the values bound to the variables in the \(\text{pat}_i\) and the rest back into one view.

The conditional operations $\text{ifS}$ and $\text{ifV}$ choose between two statements \(b_1\) or \(b_2\) according to a boolean expression \(e\), and both of them are translated into case statements in BiGUL ($\text{CaseS}$ and $\text{CaseV}$ respectively).

### 5.2.5 Source-view alignment

As described toward the end of Sec. 4, the core alignment operations $\text{alignpos}$ and $\text{alignkey}$ correspond closely to BiGUL’s $\text{Align}$ operation. The

\[
\begin{align*}
\vdash \text{\text{pat}} & \Rightarrow (\text{\text{hp}}(\Gamma_{\text{\text{pat}}})) \\
\vdash \tau & \Rightarrow (\emptyset) & \vdash x \text{\text{as}} \tau & \Rightarrow (\text{\text{hx}}, \{(x, \text{\text{hx}})\}) \\
\vdash \text{\text{pat}} & \Rightarrow (\text{\text{hp}}, \Gamma_{\text{\text{pat}}}) \\
\vdash () & \Rightarrow (\emptyset) & \vdash n[\text{\text{pat}}] & \Rightarrow (hm \text{\text{hp}}, \Gamma_{\text{\text{pat}}}) \\
\vdash \text{\text{pat}}_1 & \Rightarrow (\text{\text{hp}}, \Gamma_{\text{\text{pat}}_1}) & \vdash \text{\text{pat}}_2 & \Rightarrow (\text{\text{hp}}, \Gamma_{\text{\text{pat}}_2}) \\
\vdash \text{\text{pat}}_1, \text{\text{pat}}_2 & \Rightarrow ((\text{\text{hp}}, \text{\text{hp}}), \Gamma_{\text{\text{pat}}_1} \cup \Gamma_{\text{\text{pat}}_2})
\end{align*}
\]

Fig. 14 Compilation of patterns.
compilation is thus straightforward, turning bidirectionalizable updates into BiGUL programs and expressions and unidirectional updates into functions. Notably, the matching-by-position and matching-by-key variants can be expressed by providing suitable matching predicate functions to Align.

5.3 Compilation of expressions, paths and patterns

Finally, Fig. 15 shows the rules for compiling expressions and paths. The judgement $\Gamma_{\text{var}} \vdash e \Rightarrow hexp$
$e \Rightarrow hexp$ says that the expression $e$ is compiled into a Haskell expression $hexp$ under the environment $\Gamma_{\text{var}}$, which maps from BiFluX variable names to distinct, fresh Haskell variable names. In the rule for element expressions $n[e]$, $hn$ is the Haskell datatype constructor name for the given element $n[e]$ computed from an ambient type environment. A path $p$ is compiled into a Haskell function $f$, which is applied to the current focus. The notation $\Gamma_{\text{var}} \triangleright (x,hx)$ denotes an environment obtained by removing $x$ from $\Gamma_{\text{var}}$ (if any) and then adding $(x,hx)$. Like source paths in Sec. 5.2.1, we also have another set of translation rules $\Gamma_{\text{var}} \vdash f \in \tau \Rightarrow f$ that enumerate all the types, which are used in the compilation of for expressions and paths of the form $p_1 / p_2$.

6 Related Work

6.1 XML update languages

Several XML update languages have been proposed, including (among many others) XQuery! [10], FLUX [4] and the standard W3C XQuery Update Facility [24]. Even though the specification style, expressiveness and semantics of the XML updates that can be written may vary significantly, they all focus on updating XML documents in-place, i.e. updating selected parts of an XML document, keeping the remaining parts of the document unchanged. This means that update programs can be seen as unidirectional transformations that insert, delete or replace elements in a source document and produce an updated document conforming to a new target type. XML updates in BiFluX are different in that they determine how to update a source document (using some view information) while preserving its source type, and this is enforced by the type system.

6.2 XML view updating

In [7], the author studies the problem of updating XML views of relational databases by translating view updates written in the XQuery Update Facility into embedded SQL updates. The work of [16] supports updatable views of XML data by giving a bidirectional semantics to the XQuery Core language. The semantic bidirectionalization technique of [18] interprets various XQuery use cases as BXs by encoding them as polymorphic Haskell functions. The Multifocal language [20] allows writing high-level generic XML views that can be applied to multiple XML schemas, producing a view schema and a lens conforming to the schemas. In the four approaches, the programmer writes a view function and the system derives a suitable view update translation strategy using built-in techniques that cannot be configured. In BiFluX, the programmer writes an update translation strategy directly as an update (over the source) and the system derives the uniquely related query.

6.3 Bidirectional XML languages

Many bidirectional programming languages support tree-structured or XML data formats. Two popular bidirectional XML languages are XSugar [3] and biXid [14], which describe XML-to-ASCII and XML-to-XML mappings as pairs of intertwined grammars. While XSugar restricts itself to bijective grammars, biXid programs describe nondeterministic specifications and are thus inherently ambiguous. Most functional bidirectional programming languages are based on lenses [8] [21] [22] [13], and follow a combinatorial style that puts special emphasis on building complex lenses by composition of smaller combinators. Depending on the choice of combinators, lens languages can become very powerful at specifying application-specific behavior [22] [1] [21]. However, their lower-level nature also induces a more cumbersome programming style that makes it impractical and often unintuitive for users to build non-trivial BXs by piping together several small, surgical steps.

BiFluX features a new programming by update paradigm, which enables the high-level syntax of relational languages such as XSugar and biXid while providing a handful of intuitive update strategies. Remember the huge gap between our high-level BiFluX language (pattern matching, procedures, etc.) and the lens-based BiGUL language that gives it semantics. The most significant innovation in BiFluX is thus the declarative surface language used to specify BXs as bidirectional update programs, at a notably higher-level of abstraction than lens-based functions.
7 Conclusion

In this paper, we propose a novel bidirectional programming by update paradigm that comes to light from the idea of extending a traditional update language with bidirectional features. Under the new paradigm, programmers write bidirectional updates that specify how to update a source document by embedding view information. To demonstrate the potential of this paradigm, we designed BiFluX, a high-level bidirectional XML update language. We have shown that programming in BiFluX enjoys a better trade-off between the expressiveness and declarativeness of the written bidirectional programs, by allowing users to write directly, in a friendly notation and at a nice level of abstraction, a view update translation strategy that gives rise to a well-behaved BX.

As future work, we are still seeking to extend BiFluX so as to further increase the flexibility of BiFluX programming. For example, during alignment, the programmer might wish to specify the exact source positions into which unmatched views are inserted, but currently there is no way to do that with BiFluX; this requires us to go back to the basic BX theory and then come up with a new syntax for such specifications. We also plan to provide more static guarantees to BiFluX by incorporating existing path-query static analyses, implement more powerful pattern type inference algorithms to avoid excessive annotations, and extend the class of bidirectional updates that can be written by integrating user-defined lenses for defining source and view focuses. We also plan to improve the efficiency of our prototype for large XML databases by exploring optimizations to the underlying BiGUL language, including incremental update translation.

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